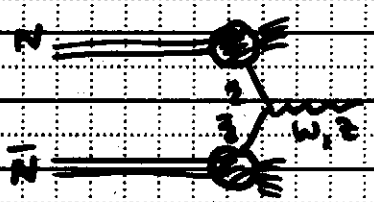
R. D. Ball
NuFact 2000
Monterey

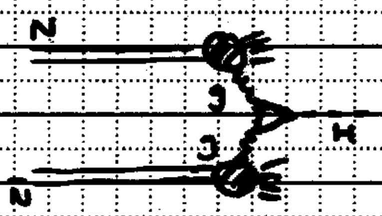
Parton Flavor Decomposition

- DIS + ν-DIS.
- Flavor decomposition
- Global fits
- Errors
- Polarized Flavours.

Why do we need precise determinations of pdfs?

- pdfs + α_s necessary input to hadron collider xsec





etc.

eg errors on W xsec at LHC ~5%
due mainly to α_s + $q, \bar{q}$ distn uncertainties

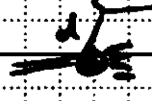
Need reliable pdfs to predict xsec for new processes
" " " to control QCD bkds.

Also need error estimates on these pdfs
(cf HERA high Q^2 + CDF high p_T jets)

- CKM matrix elements V_{cd} + V_{cs}

$|\Delta V_{cd}| = 17\%$ } now — 3% } after improving new tech — $O(1\%)$ } at ν-fac
$|\Delta V_{cs}| = 20\%$ } — 2% } — $O(\text{few }\%)$ }

Measure at ν-fac (in ν-DIS) by tagging charm in final state

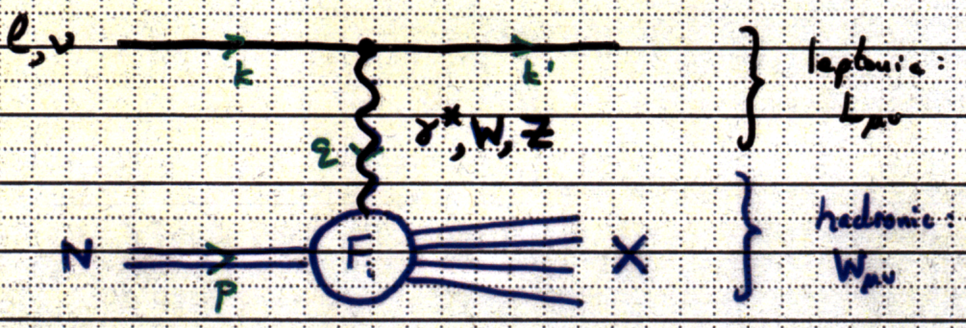


Need accurate estimates of $d(x)$, $\bar{d}(x)$, $s(x)$ + $\bar{s}(x)$.

- Polarization expts
  - new insight into pQCD
    eg 'spin crisis' : axial anomaly
  - may be needed some day to determine chiral structure of interactions beyond SM.

J.M. Virey

(unpolarized) **DIS x-sections.**



$$Q^2 = -q^2 = -(k-k')^2 \qquad W^2 = (q+p)^2 = Q^2\left(\frac{1-x}{x}\right)$$

$$x = Q^2/2p\cdot q \qquad y = p\cdot q/p\cdot k$$

$L_{\mu\nu}$ calculable (neutral current or charge current)

$W_{\mu\nu}$ not calculable: decompose into "structure functions" F_i:

$$\left.\begin{aligned} W_{\mu\nu} = {} & \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x, Q^2) \\ & + \left(p_\mu - \frac{p\cdot q}{q^2} q_\mu\right)\left(p_\nu - \frac{p\cdot q}{q^2} p_\nu\right)\frac{1}{p\cdot q} F_2(x, Q^2) \end{aligned}\right\} \text{parity cons. C-even}$$

$$- \frac{i}{p\cdot q} \epsilon_{\mu\nu\alpha\beta}\, p^\alpha p^\beta\, F_3(x, Q^2) \qquad \text{parity violating C-odd.}$$

Then

$$\frac{d^2\sigma^{eN}}{dx\,dy} \sim xy^2 F_1(x, Q^2) + (1-y) F_2(x, Q^2)$$

$$\frac{d^2\sigma^{\nu N}}{dx\,dy} \sim xy^2 F_1^\nu(x, Q^2) + (1-y) F_2^\nu(x, Q^2) - xy\left(1-\frac{y}{2}\right) F_3^\nu(x, Q^2)$$

$$\frac{d^2\sigma^{\bar\nu N}}{dx\,dy} \sim xy^2 F_1^{\bar\nu}(x, Q^2) + (1-y) F_2^{\bar\nu}(x, Q^2) + xy\left(1-\frac{y}{2}\right) F_3^{\bar\nu}(x, Q^2)$$

Can disentangle 8 independent structure fns for every target.

pQCD evolution "Altarelli - Parisi eqns."

All pdfs $q_i, \bar{q}_i, g$ depend on x and Q^2

Once pdf is fixed at one scale Q_0^2, dependence on $Q^2 \neq Q_0^2$ is predicted by pQCD.

Singlet: $$\frac{d}{d\ln Q^2}\begin{pmatrix}\Sigma \\ g\end{pmatrix} = \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Sigma \\ g\end{pmatrix}$$ ie mixing with gluon.

Nonsinglet: $$\frac{d}{d\ln Q^2} q_i^+ = P_+ \otimes q_i^+ \qquad i = 3, 8, 15$$

Valence $$\frac{d}{d\ln Q^2} q_i^- = P_- \otimes q_i^- \qquad i = 1, 3, 8, 15.$$

Compute spl fns in pert th: $P = \alpha_s \underset{LO}{P^0} + \alpha_s^2 \underset{NLO}{P^1} + \dots$

At LO $P_{qq} = P_+ = P_-$, but not at NLO.

Use Q^2 dependence
- to test QCD → fig.
- to determine $g(x, Q^2)$ (or measure $F_L = F_2 - 2x F_1$) → fig.
- to measure α_s → fig

<u>Sum Rules:</u>

$$\int_0^1 dx\,(u - \bar{u}) = 2 \qquad \int_0^1 dx\,(d - \bar{d}) = 1 \qquad \text{Valence (Adler)}$$

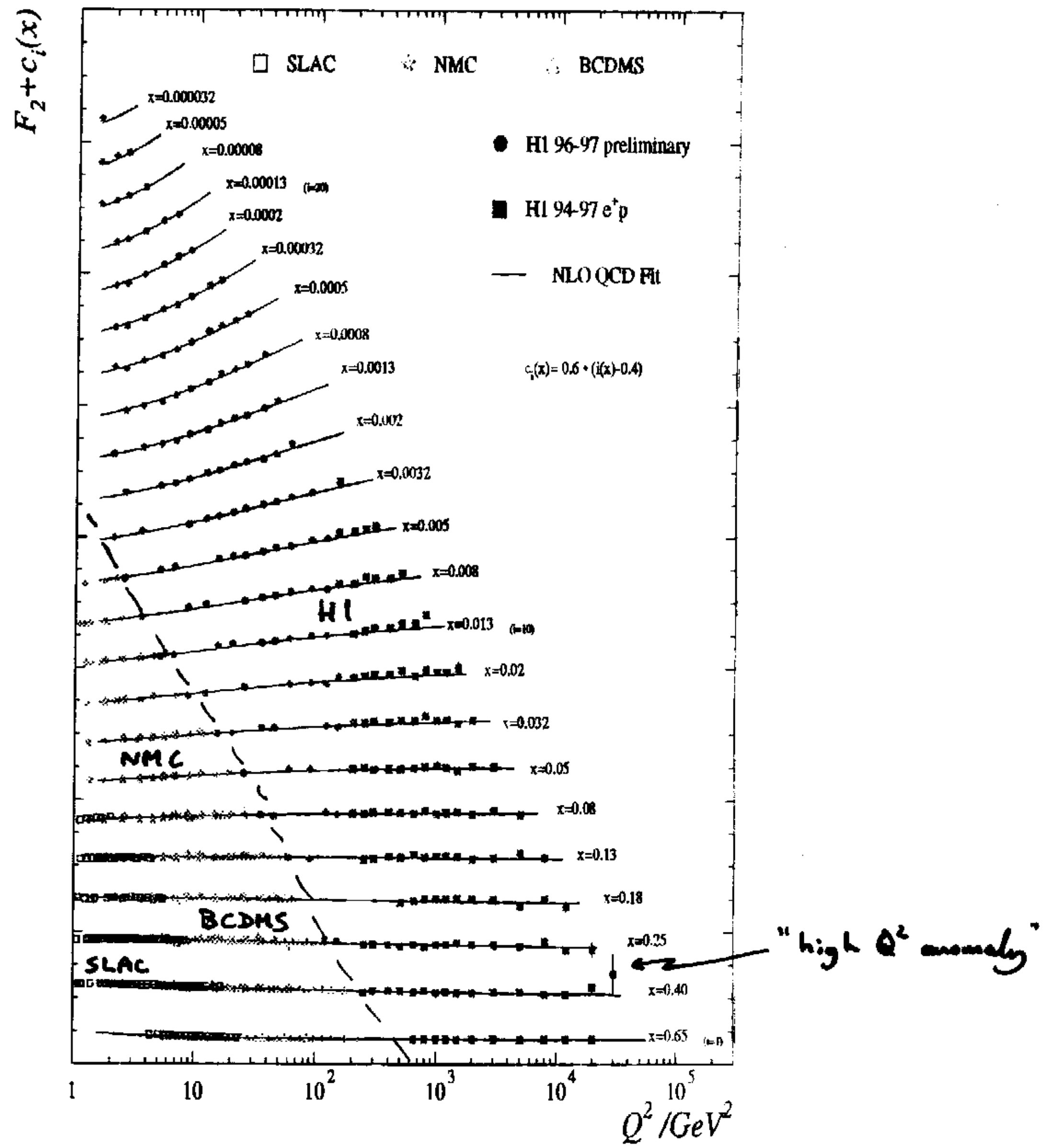
$$\int_0^1 dx\,(s - \bar{s}) = 0 \qquad \int_0^1 dx\,(c - \bar{c}) = 0 \qquad \text{CVC}$$

$$\int_0^1 dx\,(x\Sigma + xg) = 1 \qquad \text{Momentum.}$$

The "State of the Art":

NLO evolution of F_2^p

Huge kinematic coverage : ~1500 data points

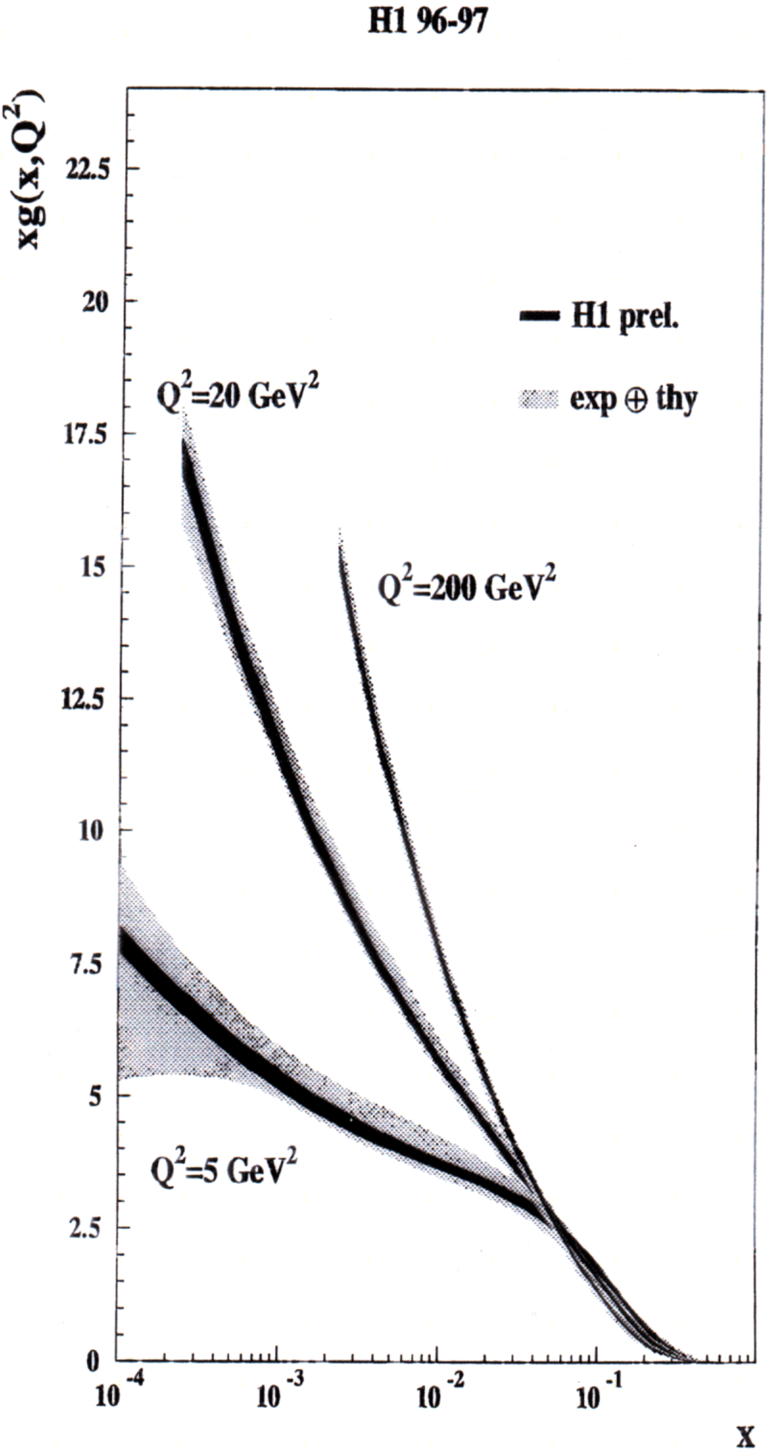


This is <u>not</u> merely a fit : QCD is predictive!

Pure NLO pQCD amazingly accurate over whole kinematic range

$\chi^2/d.o.f. = 0.99$ (with correlated errors)

Determination of the gluon (from scaling violations)



Gluon determined very precisely without need for data from less inclusive processes except at large x ($\gtrsim 0.1$)

(here need prompt γ, jets, etc.....)

From xsec to pdfs.

To determine pdfs need to do global pQCD fit to xsecs or structure fn data.

Desiderata:

- accurate treatment of data & their errors

  (in particular correlations of exptal systematics must be included, & propagated through into errors on pdfs)

- accurate treatment of theory
  - NLO, preferably NNLO....
  - heavy quarks, particularly near threshold.
  - resummation of threshold logs. (at large x)
  - resummation of small x logs.
  - higher twist
  - TMC
  - nuclear corrections etc.

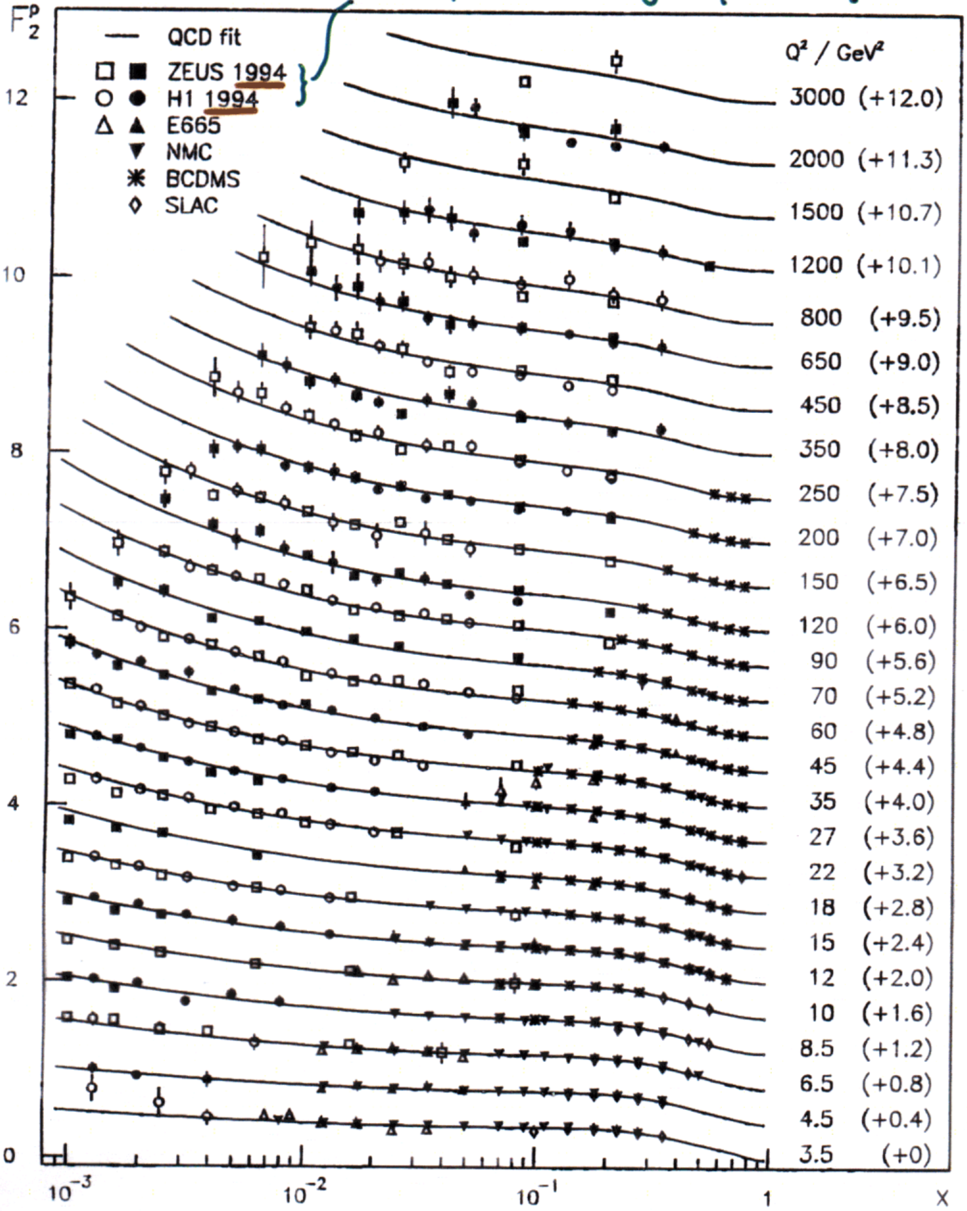
- accurate methodology

  (in particular the results should not depend on the choice of parametrization of the input distbn, or assumptions about the nature of the error propagation).

A Global fit to determine pdfs with errors. I

M. Botje hep-ph/9912439
(ZEUS)

data after 1994 not yet published!



+ E866 (DY in pp → pd)

+ F_2^d (SLAC, BCDMS, NMC)

+ $F_3^{\nu Fe}$ (CCFR) ▲ $(s+\bar{s}) = \kappa(\bar{u}+\bar{d})$ CCFR

Cuts : $x > 10^{-3}$ (avoid need for proper treatment of charm)

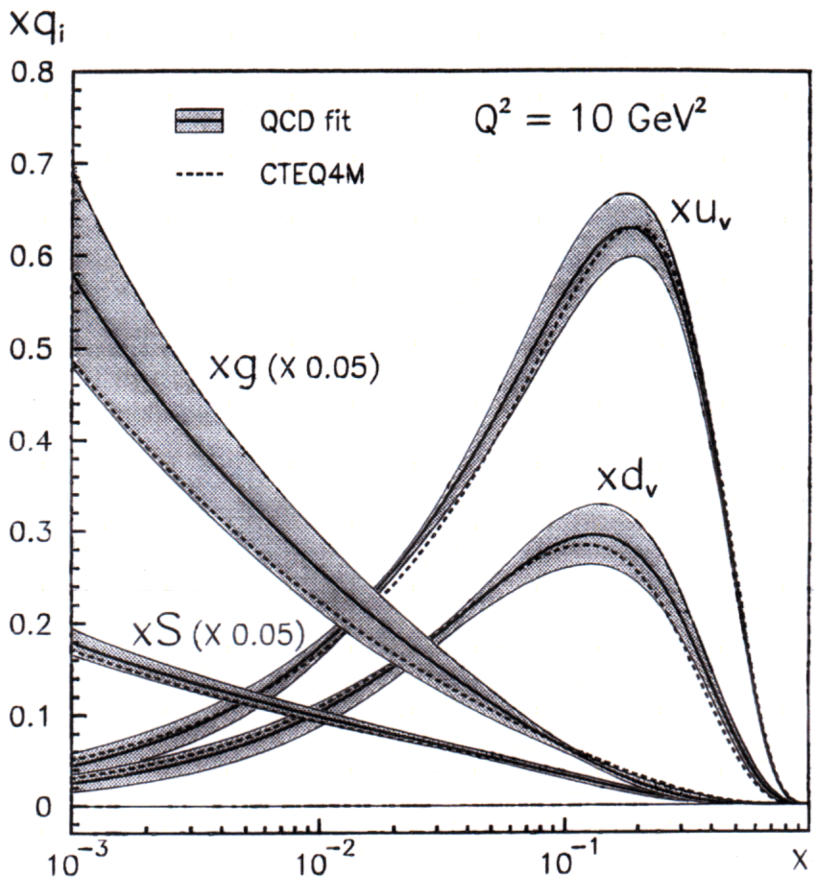
$Q^2 > 3\ \mathrm{GeV}^2$, $W^2 > 7\ \mathrm{GeV}^2$

Include HT contribution in fit.

Correct d → Fe data for nuclear effects.

The pdfs + their errors.

M. Botje
hep-ph/9912439

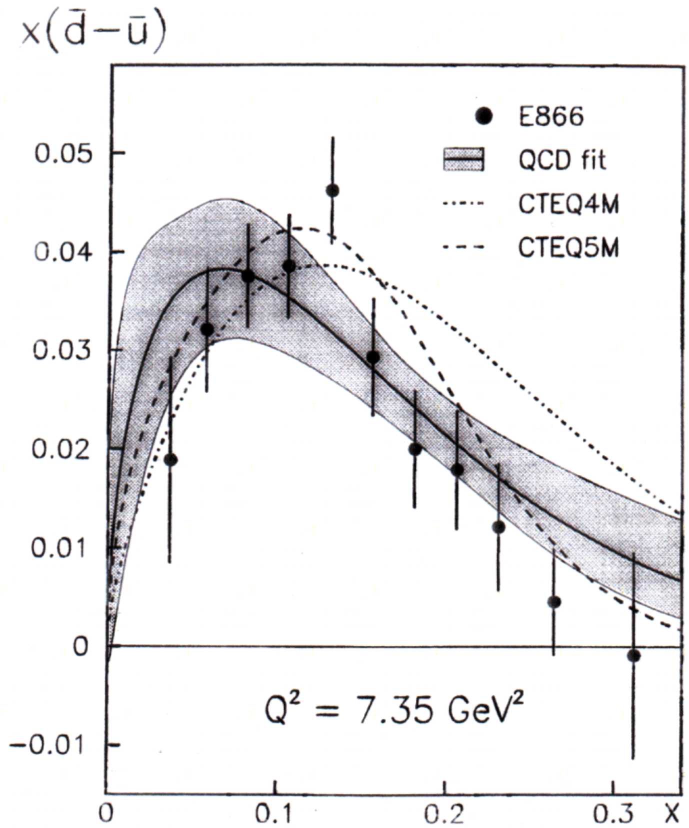


$u_v \equiv u - \bar{u}$

$d_v \equiv d - \bar{d}$

$S \equiv \Sigma = \sum_f q + \bar{q}$

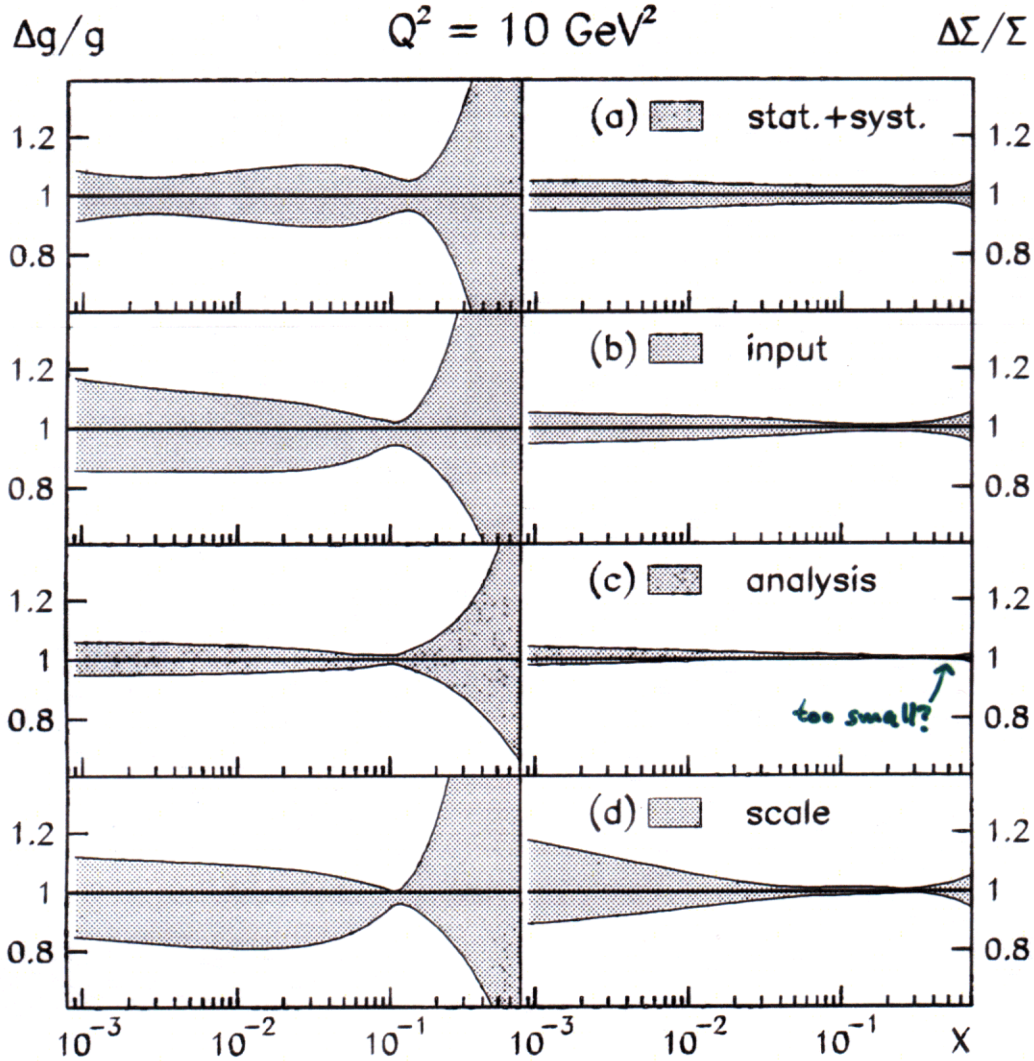
Currently the 'best' global pdfs in the world!



hep-ph/9912439.

Determining the error bands

Experimental errors (statistical + correlated systematics) propagated through to pdfs assuming all errors Gaussian.



Experimental

$\alpha_s = 0.118 \pm 0.00$!
$\Delta\kappa_s = 0.03$
Nuclear corrns
Charm thresh.

Vary cuts, input scale, some variation of parametrization

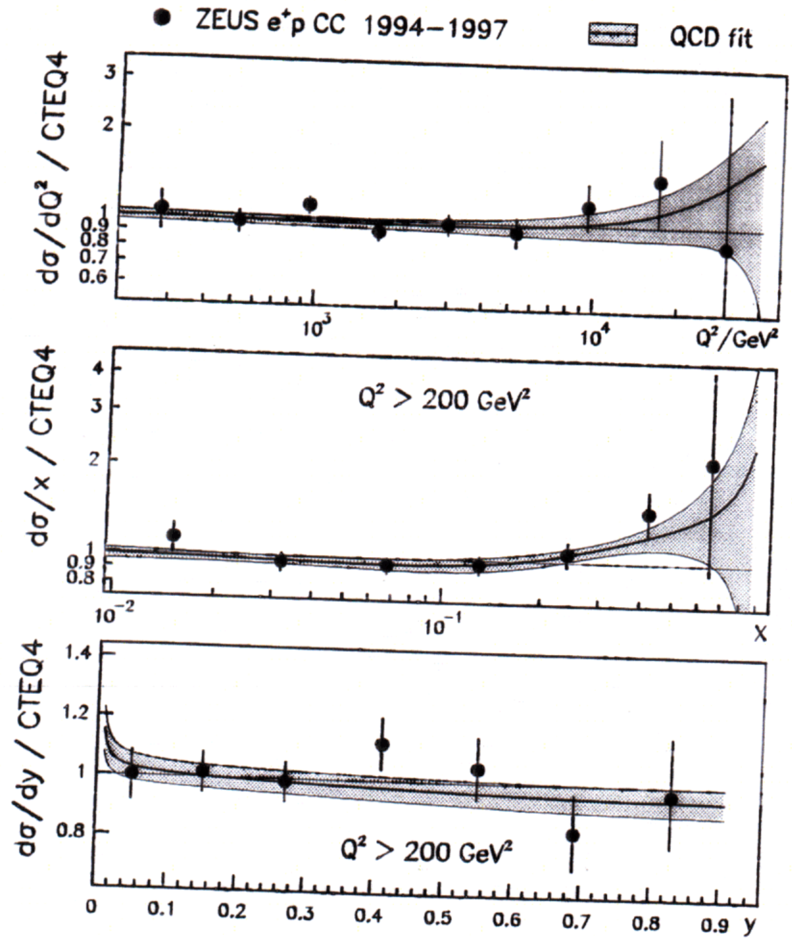
$\mu^2 \to \begin{cases} 2\mu^2 \\ \frac{1}{2}\mu^2 \end{cases}$

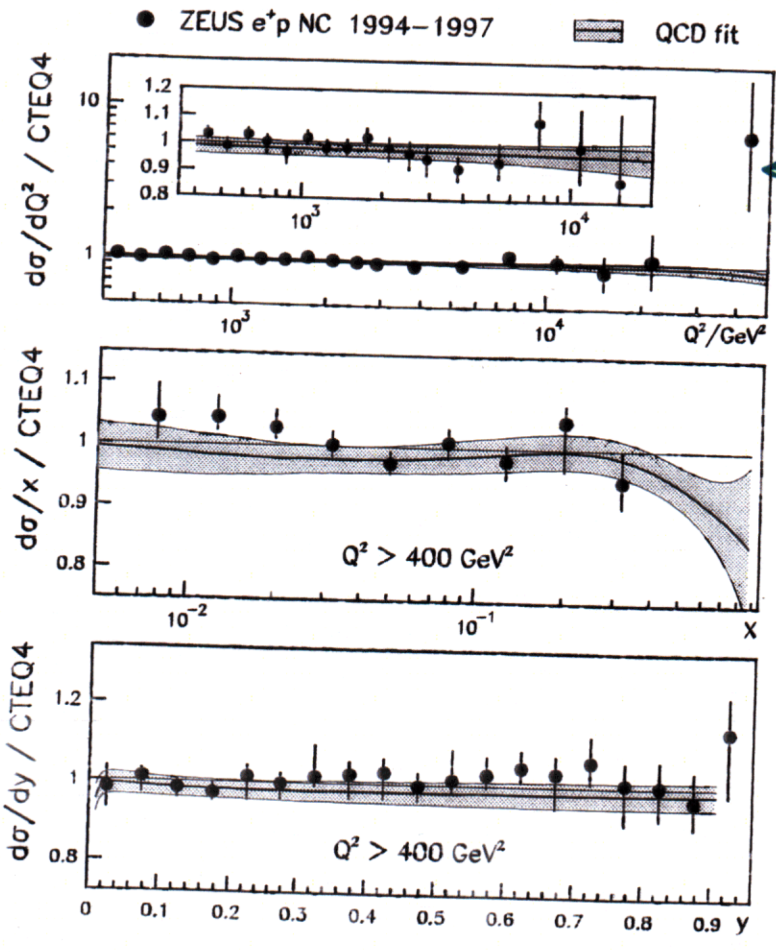
Probably underestimates errors from NNLO.

These added in quadrature for final error band

Most complete treatment of pdf errors to date.

Using these pdfs to predict HERA xsec at high Q^2



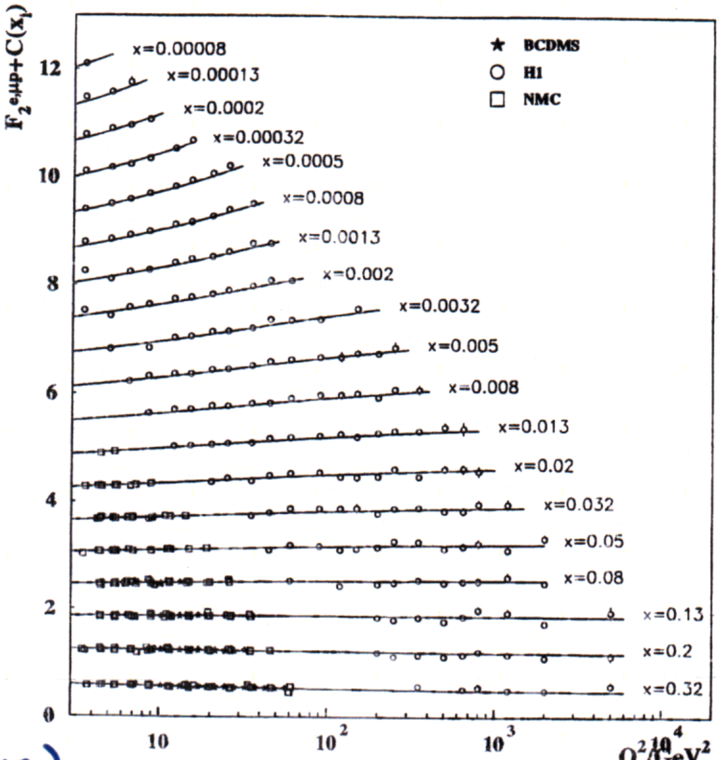


the "high Q^2 anomaly"

A Global pdf fit with errors II

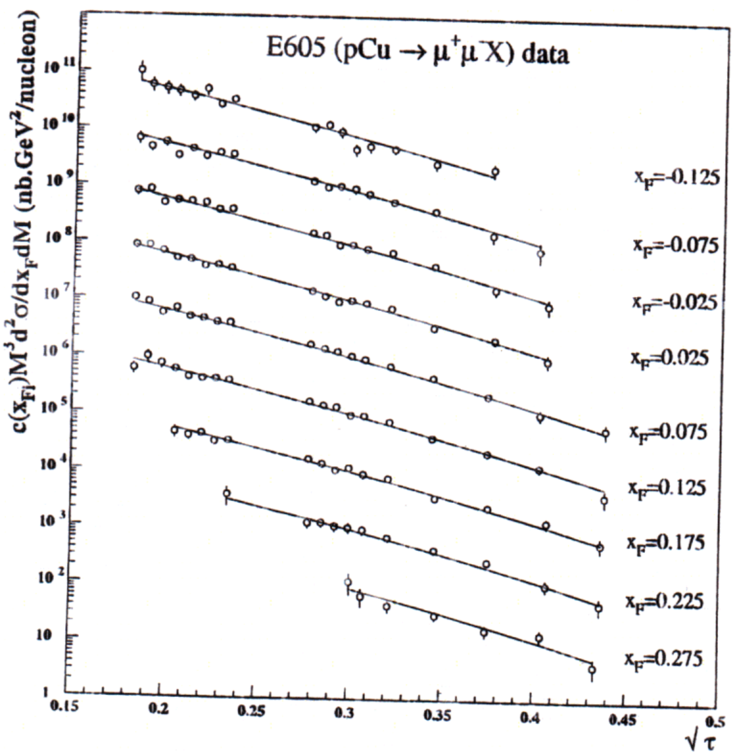
Barone
Pascaud } hep-ph/9907512
Zomer

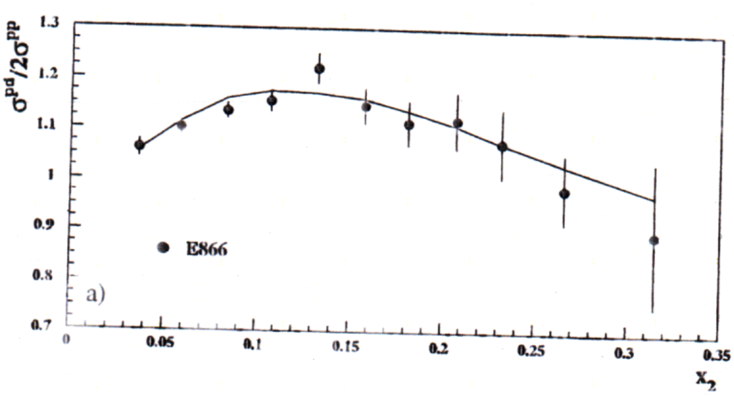
F_2^p



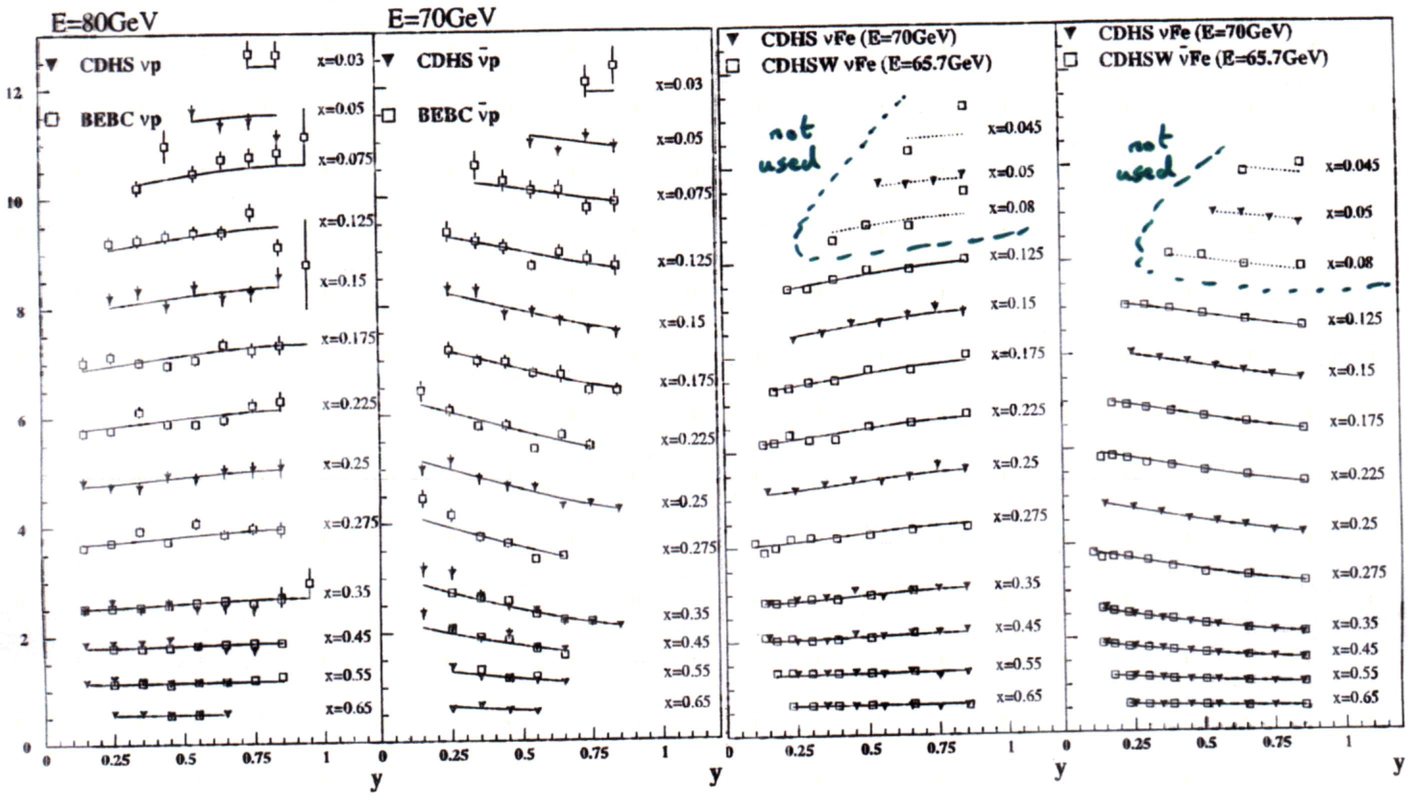
$(+\ F_2^D$ BCDMS, NMC$)$

DY :





+ ν-DIS : CDHS, CDHSW, BEBC } ν, $\bar{\nu}$ cross-sections on H, D, Fe targets.



Cuts: $Q^2 > 3.5\,\mathrm{GeV}^2$

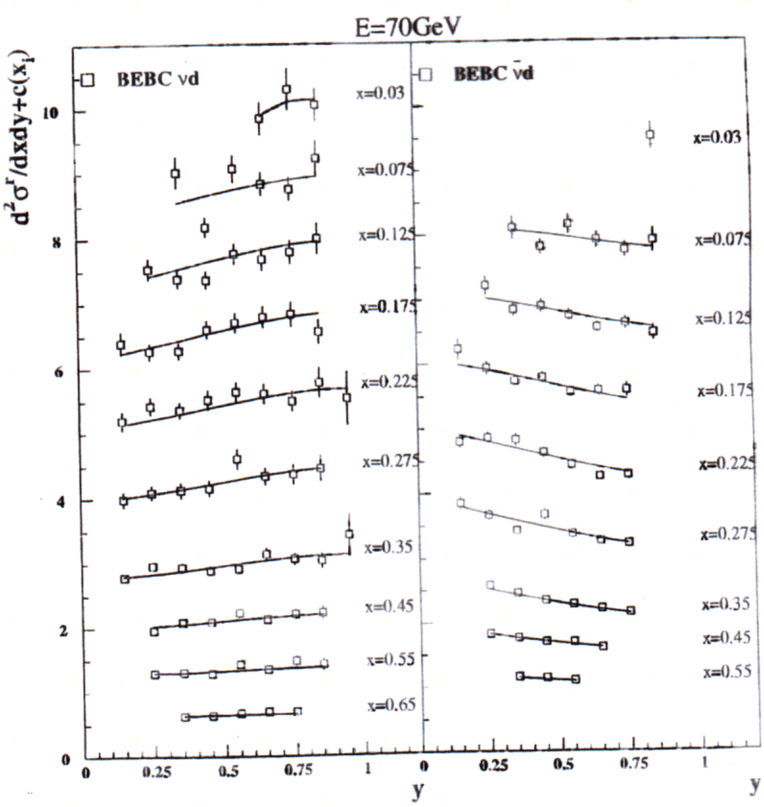
$W^2 > 10\,\mathrm{GeV}^2$

and $x > 0.1$ for Fe data.

Systematic errors, nuclear corrections re-evaluated for all the ν-xsec.

CCFR data not used because x-sec unpublished

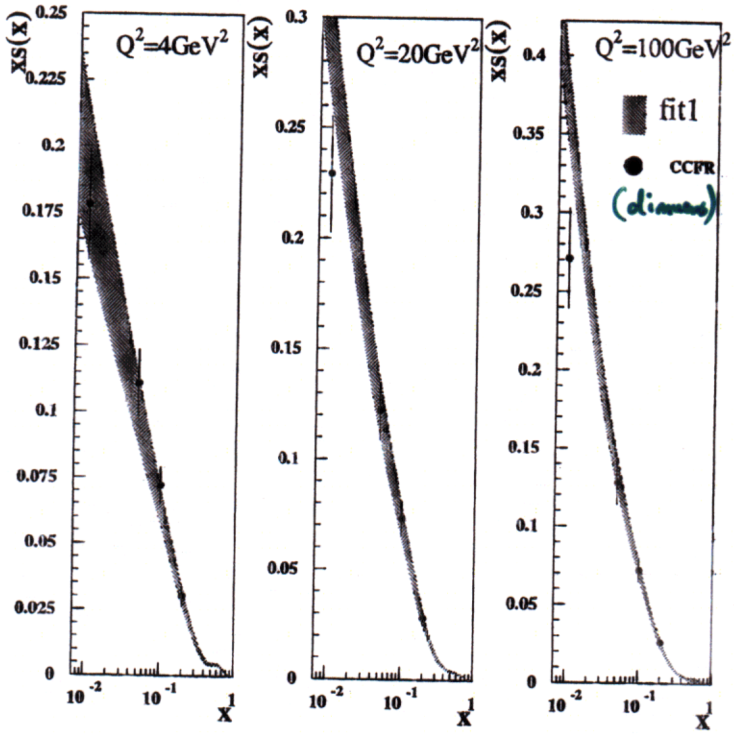
[, published $F_2^{\nu,\bar{\nu}}$, $F_3^{\nu,\bar{\nu}}$ are unreliable .... see below]



Strange pdfs (with errors)

hep-ph/9907512

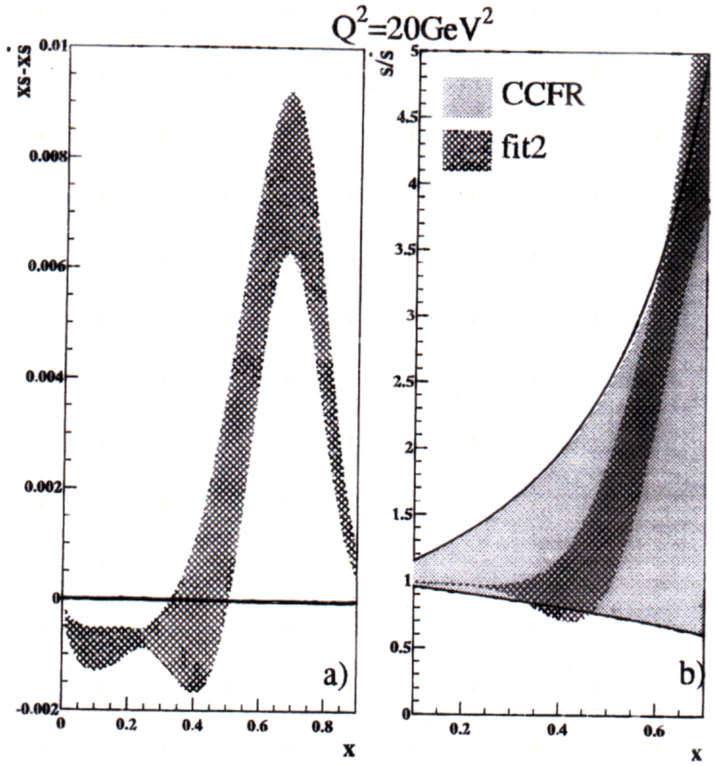
xS



Fit with $s+\bar{s}$ free, $s=\bar{s}$: $\chi^2 = 2430.8$ (2657 data pts, 44 params)

[Fit with $(s+\bar{s}) = \kappa(\bar{u}+\bar{d})$, κ free, $s=\bar{s}$: $\chi^2 = 2492.4$]

$x(s-\bar{s})$ $s/\bar{s}$



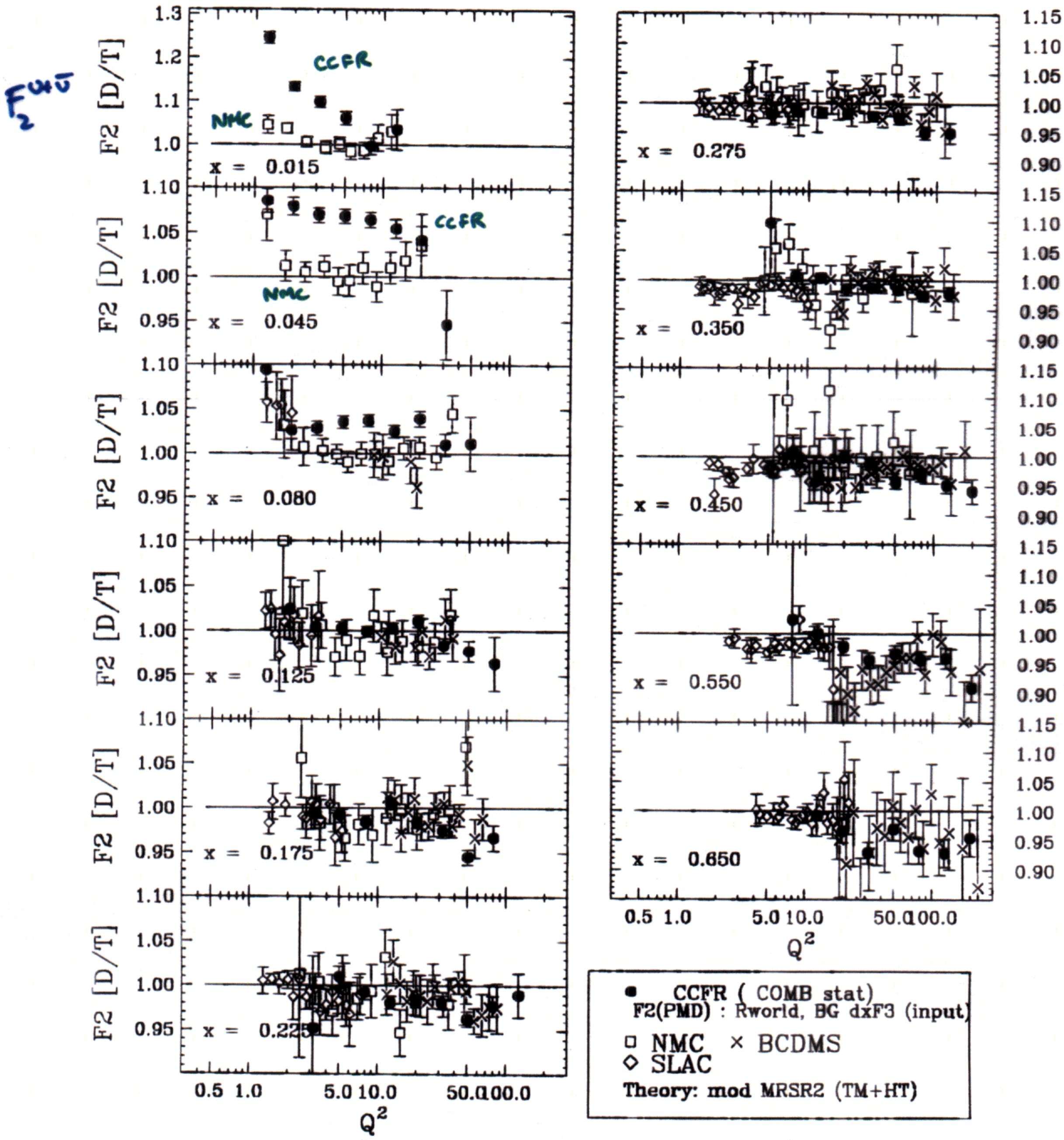
First Evidence for intrinsic strangeness ? :

Fit with $s+\bar{s}$ and $s-\bar{s}$ free : $\chi^2 = 2405.0$ [due to CDHSW ν-data at high y

Bodek et al
hep-ex/0005021.

Problems with CCFR $F_2^{\nu+\bar{\nu}}$ (1997)

At low x the $F_2^{\nu+\bar{\nu}}$ extracted from the ν-DIS xsec is inconsistent with NMC.

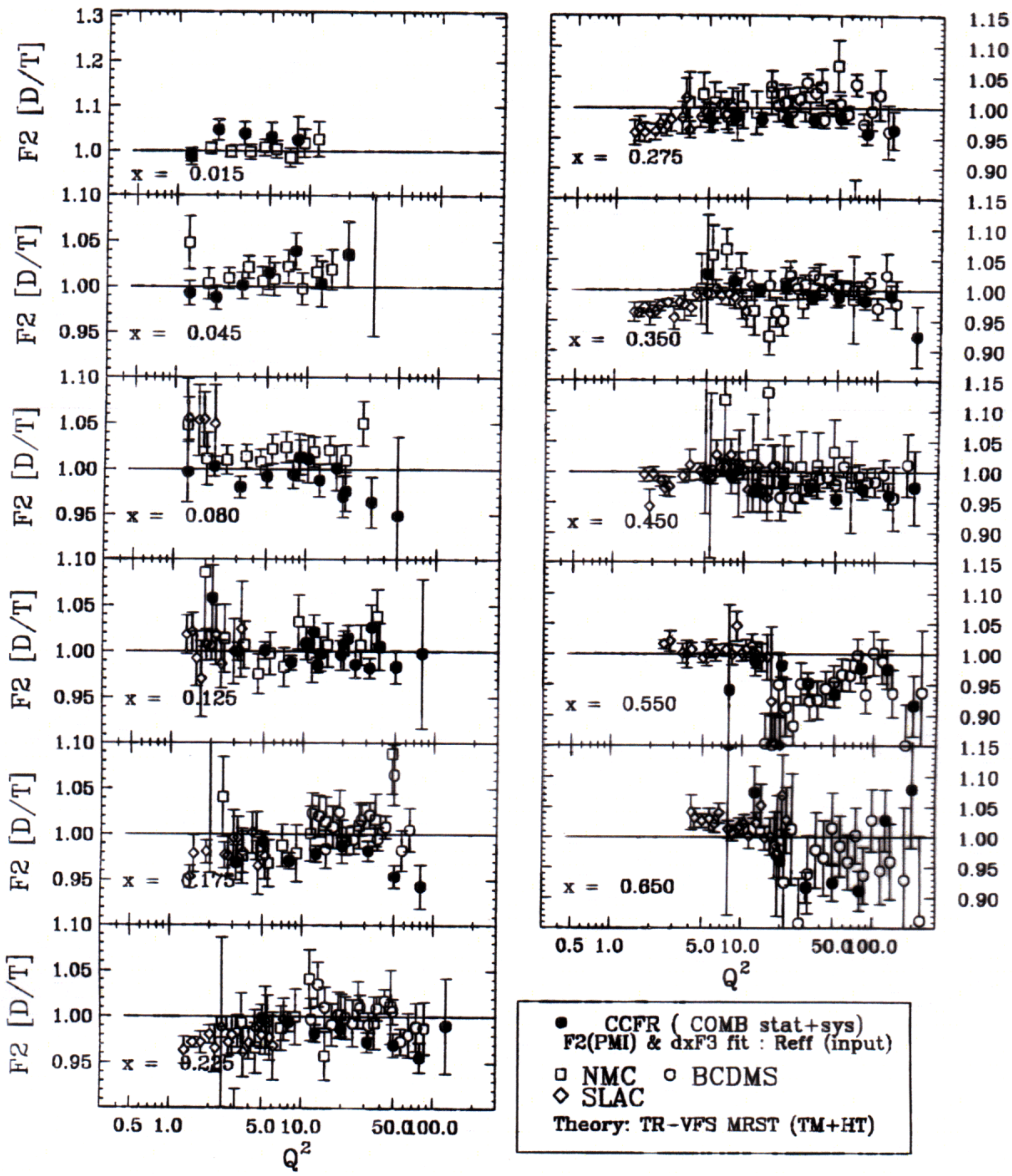


This analysis used various 'model dependent' assumptions: in particular a "slow rescaling correction" for charm + a 'LO charm production model'.

Bodek et al
hep-ex/000502

The New CCFR $F_2^{\nu+\bar{\nu}}$ (2000)

F_2 & F_3 extracted from xsec in 'model independent' way, using 2 parameter fit to y distbns.



- good news : CCFR now consistent with NMC
- bad news : CCFR F_2 changed in all x bins

1997

▲ analyses (eg α_s determination) with old CCFR data unreliable.

CCFR xsec are still unpublished....

Advantages of ν-DIS from ν-factory

- High intensity ν beams $\Rightarrow$ high statistics
  Can use H_2 + D_2 targets, rather than Fe
  (large nuclear effects $\Rightarrow$ large systematic errors)

- Clean incoming ν spectrum : reduces systematic
  error from beam energy scale (currently troublesome)

- Equal statistics for ν and $\bar{\nu}$
  (currently have # of $\bar{\nu}$ $\simeq$ $\frac{1}{3}$ # of ν)

- ν + $\bar{\nu}$ beams naturally polarised ($\because$ $\mu^{\pm}$ beams pol.)
  — would allow polarised DIS expts with ν's.
  (currently all polarised DIS is eN)

Need quantitative studies.

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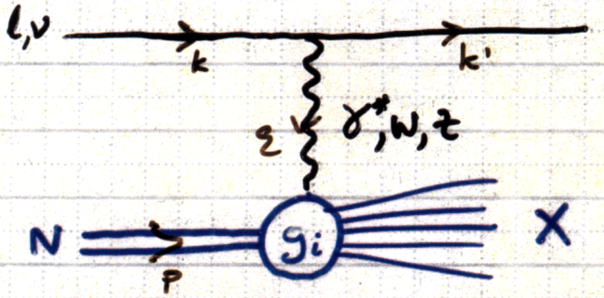
Polarized DIS x-sections



} leptonic $L^{\uparrow\uparrow}_{\mu\nu}$, $L^{\uparrow\downarrow}_{\mu\nu}$

} hadronic $W^{\uparrow\uparrow}_{\mu\nu}$ $W^{\uparrow\downarrow}_{\mu\nu}$

Asymmetry:

$$\frac{1}{2}\left(W^{\uparrow\uparrow}_{\mu\nu} - W^{\uparrow\downarrow}_{\mu\nu}\right) = i\epsilon_{\mu\nu\rho\sigma} q^\rho \left[\frac{S^\sigma}{p\cdot q} g_1(x,Q^2) + \frac{S^\sigma p\cdot q - p^\sigma S\cdot q}{(p\cdot q)^2} g_2(x,Q^2)\right]$$ parity conserving (C odd)

$$+ \frac{p^\mu S^\nu + S^\mu p^\nu}{2p\cdot q} g_3(x,Q^2) - \frac{S\cdot q}{(p\cdot q)^2} p^\mu p^\nu g_4(x,Q^2) - \frac{S\cdot q}{p\cdot q} g^{\mu\nu} g_5(x,Q^2)$$ parity violating (C even)

▲ Notation for g_3, g_4, g_5

Then

$$\frac{d^2\sigma^{eN}_{\uparrow\uparrow}}{dx\,dy} - \frac{d^2\sigma^{eN}_{\uparrow\downarrow}}{dx\,dy} \sim xy(2-y)g_1$$

$$\frac{d^2\sigma^{\nu N}_{\uparrow\uparrow}}{dx\,dy} - \frac{d^2\sigma^{\nu N}_{\uparrow\downarrow}}{dx\,dy} \sim xy(2-y)g_1^\nu + (1-y)(g_3^\nu + g_4^\nu) + xy^2 g_5^\nu$$

$$\frac{d^2\sigma^{\bar\nu N}_{\uparrow\uparrow}}{dx\,dy} - \frac{d^2\sigma^{\bar\nu N}_{\uparrow\downarrow}}{dx\,dy} \sim -xy(2-y)g_1^{\bar\nu} + (1-y)(g_3^{\bar\nu} + g_4^{\bar\nu}) + x^2y\, g_5^{\bar\nu}$$

Also transverse asymmetries, needed to determine g_2, g_3, g_4, but these suppressed by m/Q, → hard to measure.

But

$$g_2(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y) + \text{h.t.}$$ Wandzura-Wilczek

$$g_3(x) = 2x\int_x^1 \frac{dy}{y} g_5(y) + \text{h.t.}$$

$$g_4(x) = 2x\left[g_5(x) - \int_x^1 \frac{dy}{y} g_5(y)\right] + \text{h.t.}$$

} so $g_3 + g_4 = 2x g_5$, cf Callan-Gross.

So at leading twist (parton) level sufficient to measure

$$g_1,\ g_1^\nu,\ g_1^{\bar\nu},\ g_5^\nu,\ g_5^{\bar\nu}$$

Spin – Flavor Decomposition (parton model)

Assume $n_f = 4$.

$$g_1^{ep} = \sum_i e_i^2 (\Delta q_i + \Delta \bar{q}_i)$$

$$g_1^{\nu p} = \Delta \bar{u} + \Delta d + \Delta s + \Delta \bar{c} \qquad \Delta q \equiv q^{\uparrow} - q^{\downarrow}$$

$$g_5^{\nu p} = -\Delta \bar{u} + \Delta d + \Delta s - \Delta \bar{c}$$

– then for

$\nu \leftrightarrow \bar{\nu}$: $\Delta q \leftrightarrow \pm \Delta \bar{q}$ (c.c)

$p \leftrightarrow n$: $\Delta u \leftrightarrow \Delta d$ (isospin)

Decompose :

$$\Delta\Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} + \Delta c + \Delta \bar{c}$$

$$\Delta q_1^- = (\Delta u - \Delta \bar{u}) + (\Delta d - \Delta \bar{d}) + (\Delta s - \Delta \bar{s}) + (\Delta c - \Delta \bar{c})$$

$$\Delta q_3^{\pm} = (\Delta u \pm \Delta \bar{u}) - (\Delta d \pm \Delta \bar{d})$$

$$\Delta q_8^{\pm} = (\Delta u \pm \Delta \bar{u}) + (\Delta d \pm \Delta \bar{d}) - 2(\Delta s \pm \Delta \bar{s})$$

$$\Delta q_{15}^{\pm} = (\Delta u \pm \Delta \bar{u}) + (\Delta d \pm \Delta \bar{d}) + (\Delta s \pm \Delta \bar{s}) - 3(\Delta c \pm \Delta \bar{c})$$

Then

$$g_1 = \frac{7}{18}\Delta\Sigma \pm \frac{1}{6}\Delta q_3^+ - \frac{5}{54}\Delta q_8^+ - \frac{1}{54}\Delta q_{15}^+ \qquad \pm : p \text{ or } n.$$

$$g_1^{\nu} = \frac{1}{2}\Delta\Sigma \mp \frac{1}{2}\Delta q_3^- - \frac{1}{6}(\Delta q_8^- - \Delta q_{15}^-)$$

$$g_1^{\bar{\nu}} = \frac{1}{2}\Delta\Sigma \pm \frac{1}{2}\Delta q_3^- + \frac{1}{6}(\Delta q_8^- - \Delta q_{15}^-)$$

$$g_5^{\nu} = \frac{1}{2}\Delta q_1^- \mp \frac{1}{2}\Delta q_3^+ - \frac{1}{6}(\Delta q_8^+ - \Delta q_{15}^+)$$

$$g_5^{\bar{\nu}} = +\frac{1}{2}\Delta q_1^- \pm \frac{1}{2}\Delta q_3^+ + \frac{1}{6}(\Delta q_8^+ - \Delta q_{15}^+)$$

So can determine (in principle) all the quark + antiquark polarization densities by long. polarized DIS with [e], ν, ν̄ beams on p + n targets

except the "intrinsic" charm polarization $\Delta c - \Delta \bar{c}$

(use tag or calor)

pQCD evolution (polarized)

Dependence of $\Delta q, \Delta\bar{q}, \Delta g$ on Q^2 predicted by pQCD

Singlet: $$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix} = \begin{pmatrix}\Delta P_{qq} & \Delta P_{qg} \\ \Delta P_{gq} & \Delta P_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix}$$ ie mixing with Δg.

Nonsinglet: $$\frac{d}{d\ln Q^2}\Delta q_i^+ = \Delta P_- \otimes \Delta q_i^+ \qquad i = 3, 8, 15$$

Valence: $$\frac{d}{d\ln Q^2}\Delta q_i^- = \Delta P_+ \otimes \Delta q_i^- \qquad i = 1, 3, 8, 15.$$

Compute splitting fns in perturb. th.: $P = \alpha_s P_0 + \alpha_s^2 P_1 + \cdots$

At LO $P_{qq} = P_+ = P_-$ but not at NLO.

Sum rules. $$\int_0^1 dx\, \Delta q_3^+ = g_3^A$$ Independent of Q^2 PCAC measured in β-decay.

$$\int_0^1 dx\, \Delta q_8^+ = g_8^A$$ Independent of Q^2 measured in hyperon decay.

Can choose factorization schemes (AB schemes) in which $\int_0^1 dx\, \Delta\Sigma$ is also independent of Q^2: can then unambiguously give a flavor decomposition of first moments of $\Delta q + \Delta\bar{q}$.

But then $\alpha_s \Delta g$ is also large, ∵ of the axial anomaly, &

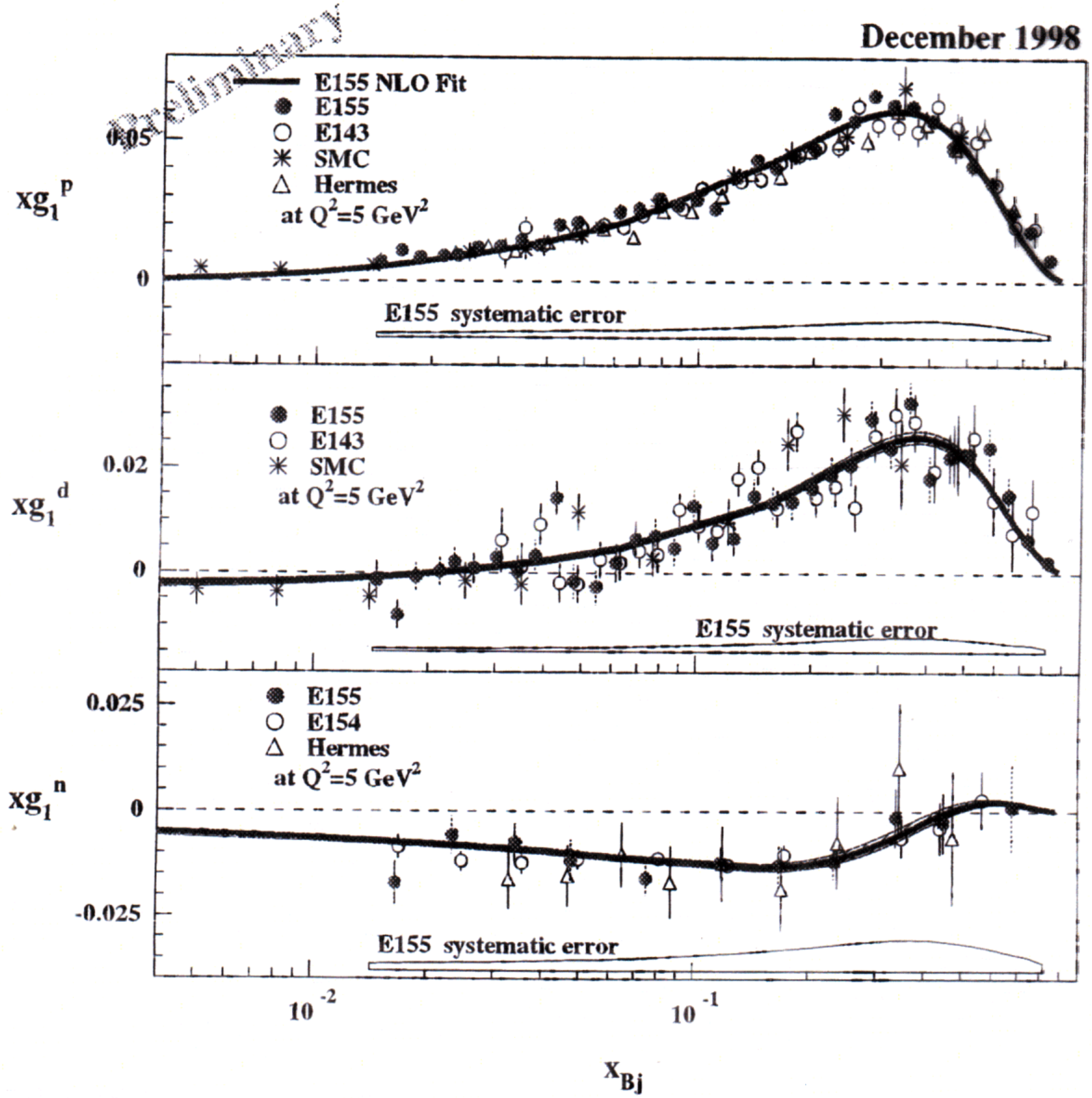
$$a_0(Q^2) = \int_0^1 dx\, (\Delta\Sigma - \alpha_s \Delta g)$$

is renormalized multiplicatively.

Smallness of a_0: "spin crisis"

World Pol. Data for g_1

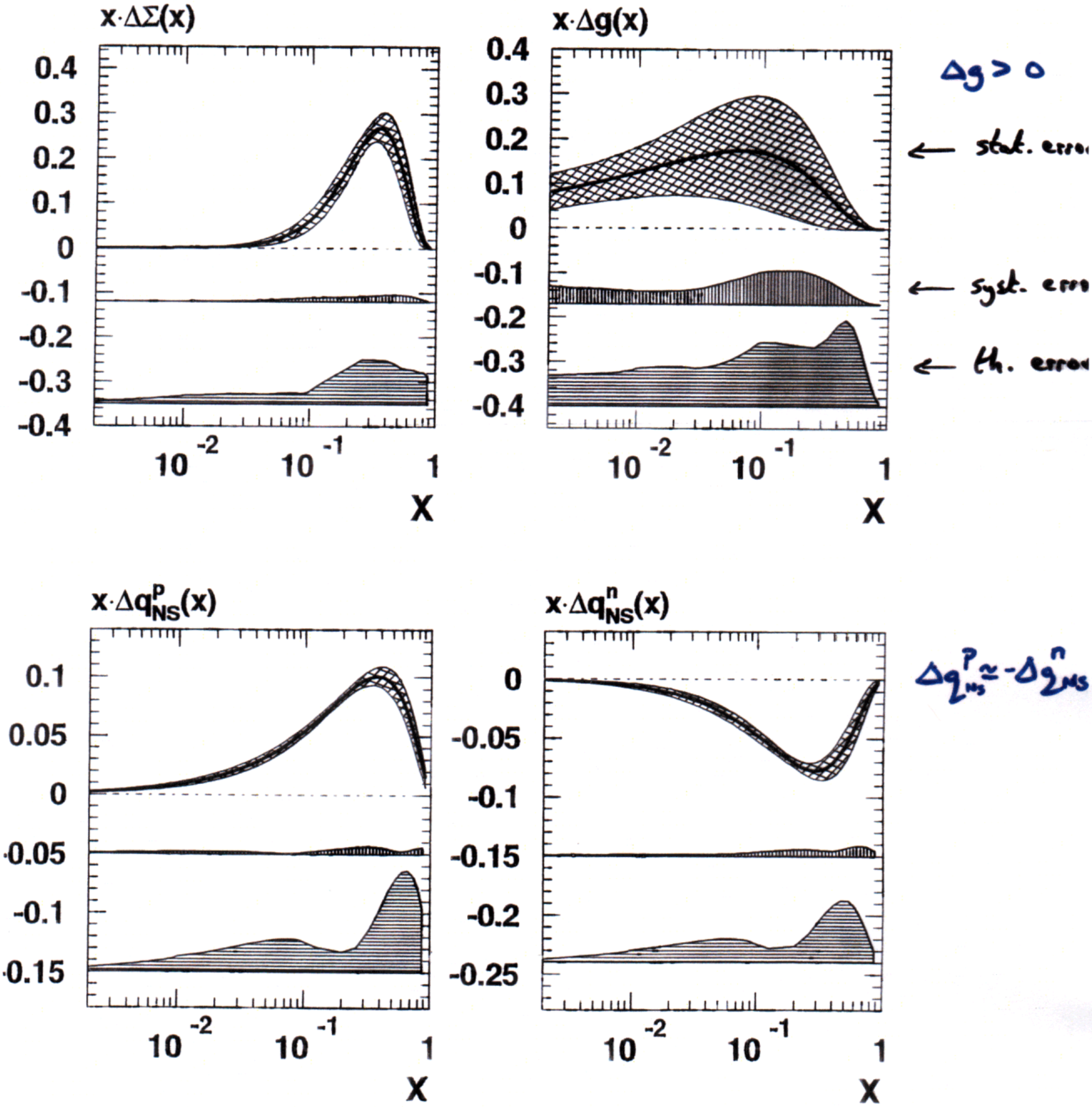
[Currently $\nexists$ data for $g_1^{\nu,\bar{\nu}}$ or g_5 : no pol. νN]



Should eventually have pol polarized DY + prompt-γ data from polarized RHIC, + charm data from COMPASS.

Polarized Parton Distributions

from global NLO fit (SMC '98)
Singlet/nonsinglet from p vs n : gluon from scaling violations



$\Delta\Sigma$ and Δq_3^+ are well determined.

Δg is poorly determined, but positive. ABFR '98.

Not possible to determine
- Δq_8^+ (ie strange polarization)
- sea/valence separation.

$a_0 = 0.10^{+0.17}_{-0.11}$: consistent with zero (but large errors)

Advantages of Polarized ν-DIS

- First moment $\int_0^1 dx\,(g_1^{\nu} + g_1^{\bar\nu}) = a_0$

ie direct measure of a_0

(compare γ^*-DIS: about 90% of g_1^{ep} is nonsinglet

$\Rightarrow$ 10% error on 1st moment $\longrightarrow$ 100% error on a_0:

$\Gamma_1 \sim 0.1 \pm 0.01 \quad \Rightarrow \quad a_0 = 0.1 \pm 0.1$)

- First moment $\int_0^1 dx\,(g_5^{\nu} - g_5^{\bar\nu}) = \mp a_3 + \frac{1}{3}(a_8 - a_{15})$ ← small, calculable

ie (combining p, n) direct measure of a_8, thus $\Delta s + \Delta\bar s$.

- $g_5^{\nu} + g_5^{\bar\nu} = \Delta q_1^- = (\Delta u - \Delta\bar u) + (\Delta d - \Delta\bar d) + \ldots\ldots$ → fig

$g_1^{\nu} - g_1^{\bar\nu} = \mp \Delta q_3^- - \frac{1}{3}(\Delta q_8^- - \Delta q_{15}^-)$

ie can determine valence quark polarizations

(these cannot be measured in inclusive γ^*-DIS)

In particular, measure $\Delta s - \Delta\bar s$: 'intrinsic' strange polarization.

Δs, $\Delta\bar s$ could also be measured by tagging charm in the final state.

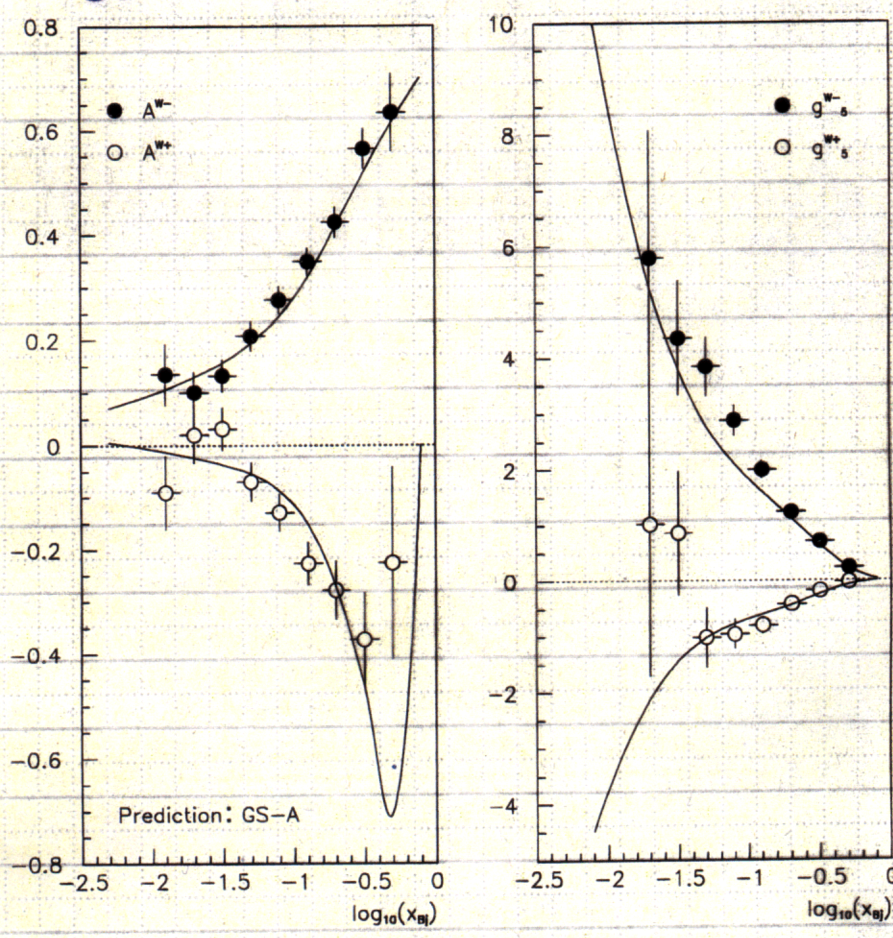
But need quantitative studies.

Gehrmann, De Roeck - Maul

Flavor Decomposition at polarized HERA

At high Q^2 ($\gtrsim 225\,GeV^2$) can extract

$$g_5^{W^-} \simeq \Delta u - \Delta\bar{d} + \Delta c - \Delta\bar{s} - \Delta\bar{b}$$
$$g_5^{W^+} \simeq \Delta d - \Delta\bar{u} + \Delta s - \Delta\bar{c} + \Delta b$$



$\mathcal{L} = 500\,pb^{-1}$

▲ very optimistic

still waiting for F_3 from CC HERA

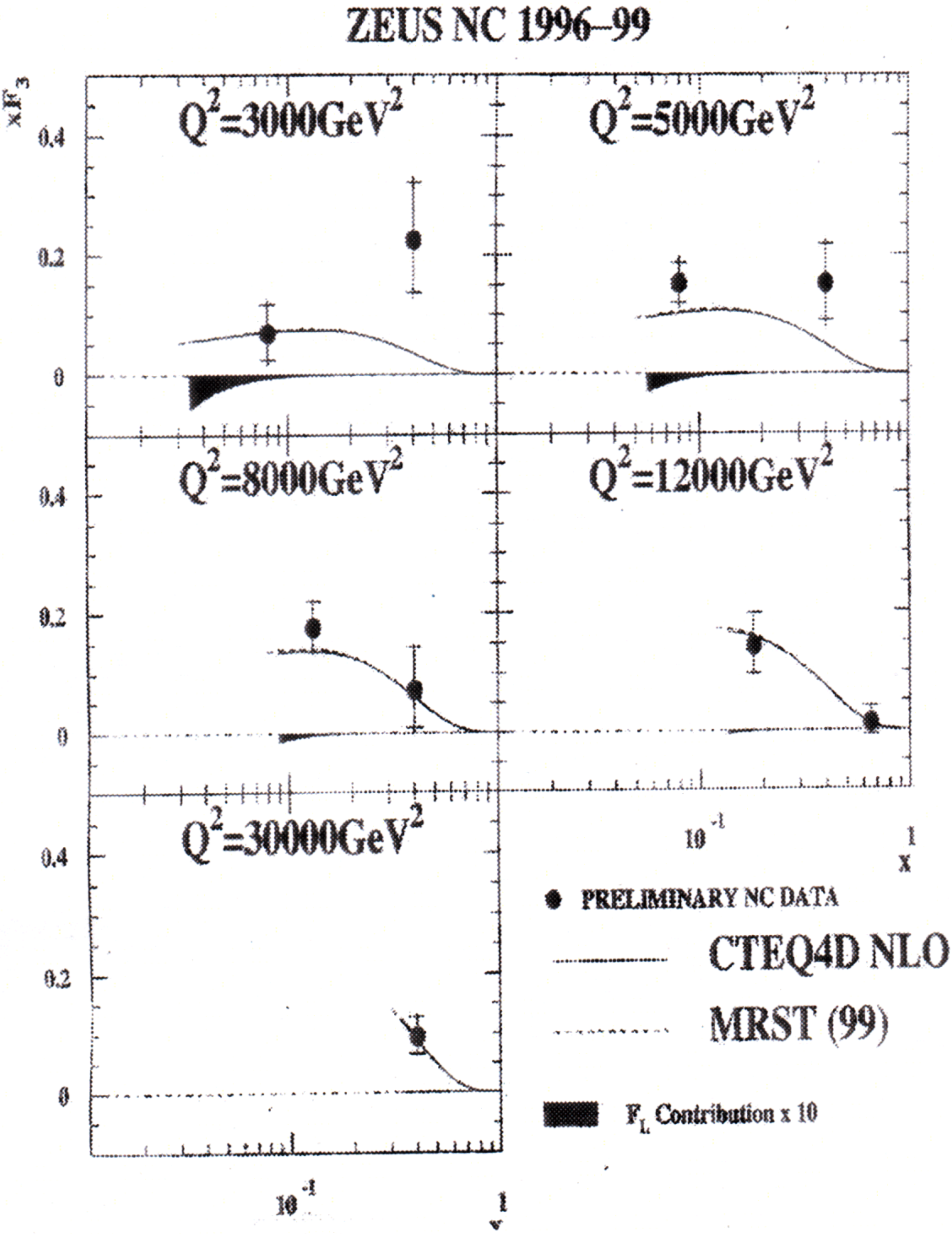
Combine with g_1 to extract $\Delta u_v, \Delta d_v$ etc at NLO

- Also Drell-Yan / vector boson production at RHIC (numerical studies?)

▲ Full flavor decomposition of first moments always has arbitrarily large scheme uncertainty (because $\Delta\Sigma$ not well defined)

No miracles!

First measurement of xF_3! at HERA



Still a long way to go.....

Summary

- A ν- factory is an ideal partonometer

- We already have the theoretical tools to analyse & exploit ~~the~~ data from ν-DIS.

  [and we're getting better all the time:
  - NNLO
  - resummations
  - parton Monte Carlos

    ⋮]

- Can we please have one soon?